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Does depleted mantle form an intrinsic part of the Iceland plume?

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[1] Icelandic basalt ranges in composition from voluminous tholeiite, erupted in the rift zones, to small-volume, mildly alkaline basalt erupted off-axis. In addition, small-volume flows of primitive basalt, highly depleted in incompatible elements, are sometimes found in the actively spreading rift axes. Relative incompatible-element depletion or enrichment in Icelandic basalt is correlated with variation in radiogenic isotope ratios, implying that the mantle beneath Iceland is heterogeneous and that the relative contribution of the various mantle components relates to eruption environment (on- or off-axis) and hence to degree of melting. Thus small-degree off-axis melting preferentially samples an enriched and more fusible mantle component, whereas more extensive melting beneath the rift axes produces magma that more closely represents the bulk Iceland plume mantle composition. The small-volume flows of depleted basalt represent melts that have preferentially sampled a depleted and more refractory mantle component. A debate has arisen over the nature of the depleted component in the Iceland plume. Some authors [e.g., *Hanan and Schilling*, 1997] argue that the depleted component is ambient upper mantle, the source of normal mid-ocean ridge basalt (NMORB) in this region. Others [e.g., *Thirlwall*, 1995; *Kerr et al.*, 1995; *Fitton et al.*, 1997], however, have used various lines of evidence to suggest that the plume contains an intrinsic depleted component that is distinct from the NMORB source. *Hanan et al.* [2000] attempt to refute the existence of a depleted Iceland plume (DIP) component through a critical evaluation of the Nb-Zr-Y arguments advanced by *Fitton et al.* [1997] and the Hf-Nd-isotopic evidence presented by *Kempton et al.* [1998]. In this paper we examine the case presented by *Hanan et al.* [2000] and conclude that their arguments are flawed. Firstly, their trace-element data set excludes data from depleted Icelandic basalt samples and so it is not surprising that they find no evidence for a DIP component. Secondly, they present two new Hf-isotope analyses of a single depleted Icelandic basalt sample and show that the data plot in their NMORB field on an εHf versus εNd diagram. However, new data allow the resolution of distinct NMORB and depleted Icelandic basalt fields on this diagram. We conclude that trace-element and radiogenic isotope data from Iceland require the existence of a DIP component.

Components: 7855 words, 4 figures, 1 table.

Keywords: Iceland; mantle plumes; basalt; radiogenic isotopes; trace elements; mid-ocean ridge.

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1. Introduction

[2] Icelandic basalt has significantly higher concentrations of highly incompatible elements than does normal mid-ocean ridge basalt (NMORB). Corresponding differences in radiogenic isotope ratios show that the elemental characteristics of Icelandic basalt must be inherited from a mantle source that is fundamentally different from that beneath normal segments of mid-ocean ridge. Interaction of a hot, deep-mantle plume with the Mid-Atlantic Ridge can satisfactorily account for the distinctive composition of Icelandic basalt, the topographic elevation of the ridge axis in Iceland, and the thickness of the Icelandic crust. Geochemical and isotopic gradients along the Mid-Atlantic Ridge north and south of Iceland have been interpreted to be the result of mixing between plume mantle and ambient depleted (NMORB-source) upper mantle [e.g., *Schilling*, 1973]. A debate has arisen, however, as to the composition of the Icelandic plume mantle. Several authors [e.g., *Hémond et al.*, 1993; *Thirlwall*, 1995; *Kerr et al.*, 1995; *Fitton et al.*, 1997; *Nowell et al.*, 1998; *Kempton et al.*, 2000; *Skovgaard et al.*, 2001] have argued that the plume contains an intrinsic, depleted component that is distinct from the NMORB source. This depleted component is recorded by basalts throughout large areas of the North Atlantic Igneous Province (NAIP), spanning 60 Ma to the present day [e.g., *Saunders et al.*, 1997]. The existence of this depleted plume component has been questioned by *Hanan et al.* [2000], who argue that the observed compositions of Icelandic basalts can be accounted for by three-component mixing between the ambient depleted NMORB-source mantle and two components that are relatively enriched in incompatible elements. According to these authors, one of the enriched components resides in the Iceland plume, while the other consists of subcontinental lithospheric mantle entrained in the local NMORB source. Whether or not depleted material occurs deep within the mantle (i.e., below the MORB asthenospheric reservoir) is clearly of importance for geodynamic models of the Earth.

[3] Incompatible-element-depleted basalts with low $^{87}Sr/^{86}Sr$ and high $^{143}Nd/^{144}Nd$ are sometimes erupted in the active rift zones of Iceland [*Schilling et al.*, 1982; *Hémond et al.*, 1993; *Hardarson and Fitton*, 1997]. These basalts have been interpreted as representing the influx of NMORB-source mantle into the melt zone beneath Iceland [e.g., *Schilling et al.*, 1982; *Hanan and Schilling*, 1997; *Hanan et al.*, 2000]. *Thirlwall* [1995], however, has shown that Icelandic basalt and North Atlantic NMORB define separate, sub-parallel arrays on a plot of $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$, suggesting that NMORB-source mantle does not mix to any significant extent with Iceland plume mantle at the present time. Depleted Icelandic basalt must, therefore, represent an intrinsic depleted Iceland plume (DIP) component [e.g., *Kerr et al.*, 1995]. A similar conclusion was reached by *Fitton et al.* [1997], who showed that, on a logarithmic plot of Nb/Y versus Zr/Y, Icelandic basalt and NMORB form separate and parallel linear arrays. Icelandic basalt has consistently higher Nb/Y at any value of Zr/Y than does NMORB, and even the most depleted Icelandic basalt samples can be distinguished from NMORB in this way. Further support for the existence of a DIP component is provided by Hf-Nd-isotope studies on Icelandic basalt [*Kempton et al.*, 2000].

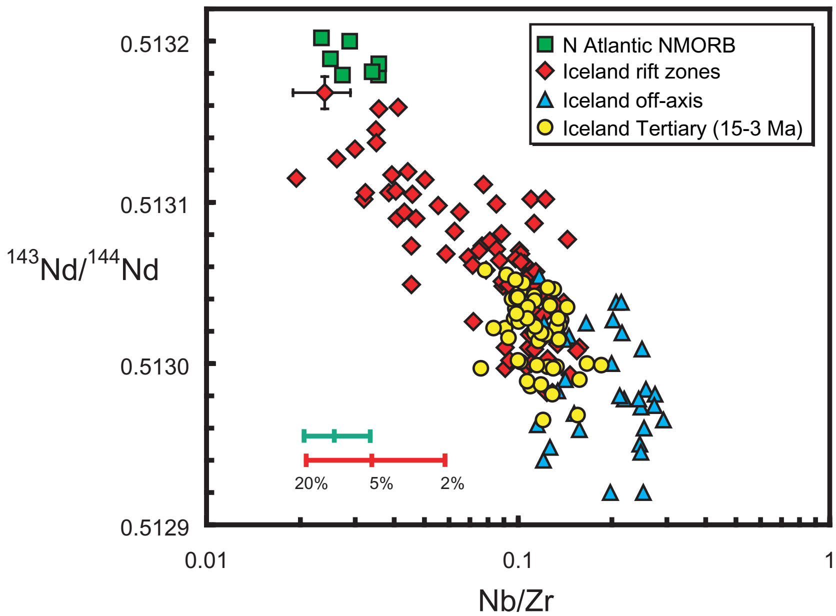

Figure 1. $^{143}Nd/^{144}Nd$ plotted against Nb/Zr for basaltic lavas (MgO >5 wt.%) from different eruptive settings in Iceland. The composition of plume-free Atlantic NMORB (95 Ma ocean floor from DSDP Site 550, off the SW UK continental margin W of Goban Spur) is shown for comparison. Error bars (2σ) are shown for one sample (±0.00001 in $^{143}Nd/^{144}Nd$; 0.47±0.1 ppm Nb, 19.4±0.2 ppm Zr). Nb/Zr error bars will become smaller with increasing Nb/Zr. The horizontal lines show the calculated variation in Nb/Zr over the range 2%–20% non-modal equilibrium melting of spinel- (green) and garnet- (red) lherzolite, using partition coefficients from *Johnson* [1998]. Data sources: neovolcanic rift-zone data from *Zindler et al.* [1979], *Nicholson* [1990], *Elliott et al.* [1991], *Furman et al.* [1991], *Hémond et al.* [1993], *Gee et al.* [1998], and *Breddam* [2002]; off-axis data from Snæfellsnes [*Hardarson*, 1993], Snæfell [*Hards et al.*, 1995], and Öræfajökull [*Prestvik et al.*, 2001]; Tertiary data from *Hardarson and Fitton* [1997]; Goban Spur data from *Kempton et al.* [2000].

Samples from Iceland and adjacent portions of the Mid-Atlantic Ridge define a field, on a plot of $^{176}Hf/^{177}Hf$ versus $^{143}Nd/^{144}Nd$, that is oblique to the main ocean-island basalt array and extends towards a long-term depleted, high-$^{143}Nd/^{144}Nd$ component with higher $^{176}Hf/^{177}Hf$ than the NMORB source.

[4] *Hanan et al.* [2000] have critically evaluated the Nb-Zr-Y and Hf-Nd-isotopic evidence in an attempt to show that the depleted end member in Icelandic basalt is the NMORB source and not an intrinsic DIP component, and they offer two principal lines of argument. Firstly, they present new Nb, Zr and Y data that show Icelandic basalt lying on a mixing curve between North Atlantic NMORB and incompatible-element-enriched basalts from the Jan Mayen Platform. Secondly, they present two new $^{176}Hf/^{177}Hf$ analyses from a single sample of Icelandic depleted basalt and show that these lie within their field for Atlantic MORB on a plot of $^{176}Hf/^{177}Hf$ versus $^{143}Nd/^{144}Nd$. The purpose of the present paper is to refute the arguments advanced by *Hanan et al.* [2000]. We shall start by assessing the nature and scale of mantle heterogeneity in the Iceland plume and then discuss its Nb-Zr-Y systematics and Hf-Nd-isotopic characteristics.

2. Elemental and Isotopic Heterogeneity in the Iceland Plume

[5] Figure 1 shows the variation of $^{143}Nd/^{144}Nd$ and Nb/Zr in Icelandic basalt. Both parameters are indices of source depletion. Nb/Zr can vary with melt fraction since Nb is more incompatible than Zr, but this alone cannot explain the order-of-magnitude variation seen in Icelandic basalt (Figure 1). Furthermore, the negative correlation between Nb/Zr and $^{143}Nd/^{144}Nd$ shows that the most incompatible-element-depleted rocks in Ice-

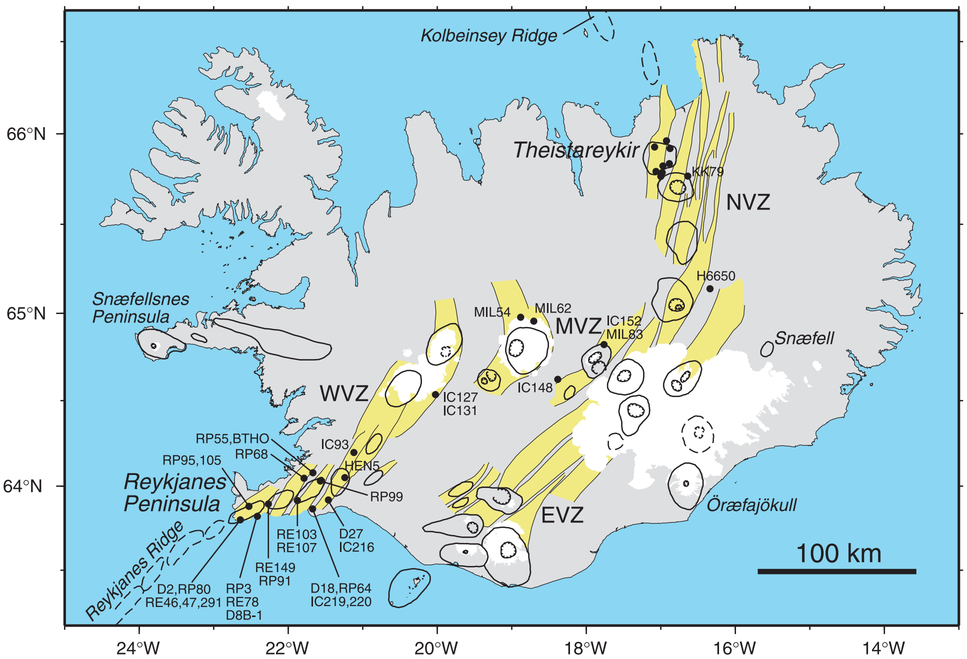

Figure 2. Distribution of depleted basalt samples (Nb/Zr < 0.06) in Iceland. Data for all of the samples are given in Table 1; individual sample localities for the *Theistareykir* volcanic system are not identified on the map. The northern (NVZ), mid-Iceland (MVZ), western (WVZ) and eastern (EVZ) volcanic rift zones are shown in yellow; volcanic systems are outlined [after *Einarsson and Sæmundsson*, 1987].

land (low Nb/Zr) were generated from regions of the mantle with the greatest time-integrated depletion in incompatible elements (high $^{143}Nd/^{144}Nd$).

[6] Another striking feature of the data in Figure 1 is the clear relationship between composition and eruption environment. Basaltic lava flows erupted from off-axis volcanic centres (Snæfellsnes, Snæfell, and Öræfajökull; Figure 2) have more enriched mantle sources (higher Nb/Zr and lower $^{143}Nd/^{144}Nd$) than do those erupted at the spreading axes. Since there is no reason to think that the mantle beneath the axes is fundamentally different in its bulk composition from the adjacent mantle beneath the rift flanks, it follows that the mantle source being tapped varies with melt fraction. This implies that the mantle is heterogeneous on a scale that is smaller than the melt zone but large enough for the effects of heterogeneity to be preserved during melting. Thus, small-degree melting beneath off-axis regions generates mildly alkaline magmas that appear to be preferentially sampling relatively enriched and more easily fusible parts of the mantle. Larger-degree melting beneath the active spreading axes generates tholeiitic magmas that will more closely reflect the bulk composition of the mantle beneath Iceland.

[7] Large-volume (>0.5 km^3) flows originating in the active rift zones have a very restricted compositional range (mean Nb/Zr = 0.11 ± 0.02 (1σ); [*Hardarson and Fitton*, 1997]), and data from them plot close to the centre of the array in Figure 1. Their mean composition and range are identical to those of lava flows forming the exposed part of the Tertiary lava pile in Iceland (Figure 1; *Hardarson and Fitton* [1997]).

[8] Significantly, the most depleted Icelandic samples in Figure 1 (Nb/Zr< 0.06) were collected from rare, small-volume (<0.2 km^3) flows of undifferentiated picrite and olivine basalt (MgO mostly > 9.5 wt.%) [*Hardarson and Fitton*, 1997]. These basalts are thought by some authors [e.g., *Schilling et al.*, 1982; *Hanan et al.*, 2000] to represent the influx of NMORB-source mantle into the melt zone beneath Iceland. The data in Figure 1 seem to support this idea since plume-free Atlantic NMORB plots at the depleted end of the array. Other authors [e.g., *Thirlwall*, 1995; *Kerr et al.*, 1995; *Fitton et al.*, 1997;

Nowell et al., 1998; *Kempton et al.*, 2000], however, disagree and regard the existence of these flows as evidence that a depleted (DIP) component forms an intrinsic part of the Iceland plume. The origin and significance of these depleted basalts will be discussed in the next section.

3. Depleted Icelandic Basalt

[9] Although rare, lava flows of depleted basalt (defined here as basalt with Nb/Zr < 0.06) are found throughout the northern, mid-Iceland, and western rift zones of Iceland. They are invariably small in volume (<0.2 km^3; *Hardarson and Fitton* [1997]), and are most abundant in the Theistareykir volcanic system in northern Iceland and on the Reykjanes Peninsula in the southwest. The international geochemical reference standard BIR-1, (from the Reykjanes Peninsula) is the best-known example of depleted Icelandic basalt. Figure 2 shows the distribution of depleted basalt in Iceland, and Table 1 gives the composition of at least one sample from each locality. Depleted basalt flows are confined to the actively spreading volcanic rift zones (NVZ, MVZ and WVZ on Figure 2), and have not been reported from the southward-propagating eastern volcanic rift zone (EVZ), where mantle upwelling is likely to be less vigorous.

[10] The very low concentrations of incompatible elements in the depleted basalts (Table 1) can best be explained by a dynamic melting process [*Elliott et al.*, 1991]. Upwelling mantle beneath the rift axes will enter the melt zone, melt will be produced and extracted, and the depleted residue will continue to melt as it decompresses further. Thus, the instantaneous melts will become progressively depleted in incompatible elements as upwelling and melting proceed. Because the most depleted basalt samples have the highest $^{143}Nd/^{144}Nd$ (Figure 1) they must represent those parts of the mantle that were the most depleted before melting started. This implies that melts produced during the advanced stages of dynamic melting are preferentially sampling the most depleted parts of a heterogeneous mantle source, and these are also likely to be the least fusible. Greater degrees of decompression and melting beneath the actively spreading rift axes will allow melting to include more of the depleted and refractory components. However, these instantaneous melts will only rarely be erupted without combining with more voluminous and less depleted melt in magma reservoirs. Because of their low concentrations of incompatible elements, the depleted melts will have little effect on the bulk incompatible-element content of magma in the reservoirs. Thus, these depleted melts can only be detected if they reach the surface as small-volume flows of relatively undifferentiated magma [*Hardarson and Fitton*, 1997].

[11] The complete absence of depleted basalt in the Tertiary lava pile (Figure 1) was noted by *Schilling et al.* [1982], who interpreted it as evidence for a recent influx of NMORB-source mantle into the melt zone beneath Iceland. However, *Hardarson and Fitton* [1997] showed that this is simply an artifact of crust-forming processes in Iceland. According to the *Pálmason* [1986] crustal accretion model, the parts of the Tertiary lava pile currently exposed in deep glacial valleys (i.e. the upper 2 km) consist of the distal ends of lava flows large enough to have flowed at least 20 km from the rift axis. Smaller flows (including small-volume flows of depleted basalt) that are emplaced closer to the rift axis are rapidly buried and carried down to the deeper and inaccessible parts of the lava pile. Depleted basalt has probably always been erupted at the rift axis but is not exposed in the accessible parts of the Tertiary lava pile.

[12] In summary, the data in Figure 1 are best explained by variable degrees of partial melting of heterogeneous mantle comprising enriched blobs or streaks set in a more refractory depleted matrix. Small-degree melting in off-axis locations (e.g. beneath Snæfellsnes) will preferentially sample the more fusible parts of the mantle, whereas more extensive melting beneath the spreading axis will sample both enriched and depleted components. Instantaneous melts produced during the advanced stages of dynamic melting will be biased towards the depleted refractory matrix. These depleted melts occasionally reach the surface as small-volume flows of primitive (high-MgO) basalt which are confined to the rift axis. The larger rift-axis flows consist of magma that has been

Table 1. Composition of Depleted (Nb/Zr < 0.06) Basalt From Iceland (Sample Localities in Figure 2)[a]

Sample	Location	SiO_2	Al_2O_3	Fe_2O_3T	MgO	CaO	Na_2O	K_2O	TiO2	MnO	P_2O_5	Nb	Zr	Y	$^{143}Nd/^{144}Nd$	Ref.
D2/11	Haleyjabunga	46.96	12.22	9.21	19.64	10.58	0.93	0.006	0.353	0.153	0.017	0.35	9.8	8.8	0.513158	1
RE46	Haleyjabunga	49.06	15.12	10.21	10.43	13.62	1.57	0.022	0.594	0.172	0.023	0.47	19.4	15.7	0.513168	2,3
RE47	Haleyjabunga	44.30	9.24	9.67	28.90	7.49	0.65	0.007	0.208	0.154	0.004	0.33	7.8	6.3		3
RE291	Haleyjabunga	47.01	13.43	9.20	17.48	11.39	1.18	0.010	0.375	0.155	0.012	0.40	14.3	11.7		3
D18	Hengill	47.79	14.16	11.25	11.73	12.24	1.64	0.040	0.916	0.184	0.040	1.4	26.1	15.4		1
D27	Hengill	47.81	15.12	9.35	13.08	12.62	1.46	0.017	0.509	0.161	0.025	0.66	15.9	15.5		1
D8B-1*	Vatnsheidarhraun	45.60	14.20	10.30	17.70	10.50	1.35	0.042	0.420	0.150	0.094	1.0	22.0	11.0	0.513049	4
RE78	Vatnsheidarhraun	46.32	13.61	9.30	18.94	10.72	1.23	0.011	0.336	0.155	0.010	0.5	11.3	12.1	0.513119	2,3
RE149	Fagradalshraun	45.91	13.98	9.01	18.29	11.23	0.98	0.004	0.281	0.140	0.005	0.2	10.3	9.2	0.513115	2
RP3	Grindavik	45.22	13.40	9.82	18.25	10.65	1.32	0.014	0.360	0.147	0.024	0.5	11.6	11.4	0.513094	4,5
RP55C	BIR-1 locality	45.37	11.69	11.53	19.64	9.59	1.27	0.025	0.670	0.171	0.030	0.7	17.8	13.3	0.513117	4,5
RP55D	BIR-1 locality	44.53	10.61	11.13	23.16	8.64	1.16	0.014	0.510	0.162	0.021	0.6	12.9	10.2		4,5
RP55E	BIR-1 locality	47.18	15.39	11.39	10.23	12.90	1.79	0.018	0.920	0.172	0.025	0.5	15.6	15.8		4,5
RP64O	Hlidarvatn	47.16	15.67	9.70	11.41	12.90	1.61	0.018	0.590	0.166	0.038	1.0	19.9	17.3	0.513114	4,5
RP68D	Heidmork	48.34	16.12	9.95	9.86	13.55	1.73	0.038	0.600	0.165	0.041	1.2	21.3	15.7		4,5
RP80D	Haleyjabunga	47.09	13.93	9.18	16.29	11.76	1.19	0.007	0.390	0.151	0.028	0.5	14.3	11.5	0.513145	4,5
RP91E	Fagradalur	47.25	14.28	10.22	14.50	12.12	1.27	0.006	0.500	0.161	0.031	0.6	17.1	12.6	0.513137	4,5
RP95C	Lagafell klift	48.02	14.94	9.03	11.59	13.60	1.43	0.006	0.480	0.151	0.029	0.53	17.0	15.1	0.513159	4,5
RP99A	Vifilsfell	48.46	15.06	10.71	9.51	13.50	1.56	0.035	0.680	0.178	0.051	1.6	26.7	16.9		4,5
RP103E	E of Kleifarvatn	48.74	16.74	9.65	10.04	13.63	1.98	0.014	0.610	0.170	0.028	0.44	21.8	17.5		4,5
RP105A	NE of Lagafell	48.69	16.46	9.00	9.91	13.85	1.49	0.016	0.500	0.153	0.038	0.7	19.0	13.9		4,5
RP107A	E of Kleifarvatn	47.44	16.23	9.43	11.60	12.83	1.62	0.014	0.550	0.157	0.034	0.6	22.9	17.1	0.513127	4,5
HEN5*	Hengill	48.70	10.80	12.10	16.20	10.60	1.14	0.030	0.660	0.170	0.020	0.9	22.0	10.0	0.513090	6
BTHO*	BIR-1 locality	48.04	15.10	11.30	9.95	13.50	1.80	0.030	0.880	0.170	0.060	0.49	12.1	16.8	0.513107	6
MIL54*	Lambahraun	47.70	16.50	11.58	8.40	13.60	2.02	0.080	1.070	0.150	0.080	2.6	44.3	20.6	0.513068	6
MIL62	Illvidrahnjukahraun	47.62	16.36	9.86	9.80	13.02	1.84	0.033	0.626	0.154	0.042	0.86	26.6	15.6	0.513106	6
MIL83*	Dvergar	48.45	16.80	10.28	10.40	12.70	2.01	0.020	0.580	0.140	0.040	0.8	25.0	14.5	0.513102	6
IC93	Mjoafell	48.16	16.48	9.68	9.68	13.05	2.02	0.033	0.871	0.155	0.050	1.8	35.7	18.4		7
IC127	Raudafell	47.86	17.54	10.44	9.76	12.11	1.95	0.040	0.689	0.157	0.043	1.6	28.4	15.6		7
IC131	Raudafell	48.12	17.64	10.42	9.78	12.17	2.15	0.042	0.697	0.157	0.044	1.6	28.2	15.3		8
IC148	East of Kistualda	48.05	15.43	10.02	11.29	12.86	1.77	0.026	0.686	0.166	0.039	1.12	25.9	16.6		7
IC152	Dvergar	47.56	17.24	10.04	9.93	12.05	2.01	0.024	0.587	0.164	0.040	0.68	24.9	16.1		8
IC216	Threngsli	47.77	14.77	9.34	14.74	12.04	1.59	0.018	0.475	0.158	0.030	0.58	18.3	14.7		8
IC219	Hlidarvatn	48.90	16.18	9.87	9.83	13.36	1.99	0.021	0.583	0.160	0.035	1.3	22.9	16.8		7
IC220	Hlidarvatn	48.77	15.88	10.07	9.58	13.50	1.90	0.022	0.606	0.168	0.031	0.84	21.5	16.3		8
H6650*	Herdubreidartogl	50.30	13.80	8.17	13.10	13.10	1.11	0.035	0.520	0.160	0.011	1.0	26.0	14.0	0.513106	6
KK79	Eilifsvotn, Krafla	50.01	14.97	10.48	7.94	13.77	1.85	0.046	0.817	0.177	0.059	2.4	40.1	19.6		9
42	Theistareykir	48.57	14.92	9.93	11.21	13.22	1.54	0.048	0.618	0.164	0.035	1.4	27.7	16.5		8
IT5	Theistareykir	46.94	13.18	11.01	15.84	11.12	1.35	0.035	0.721	0.169	0.033	1.3	28.4	12.5	0.513105	1
IT6	Theistareykir	48.54	15.66	10.68	10.60	13.13	1.64	0.045	0.884	0.182	0.043	1.7	36.2	17.3	0.513090	1
IT7	Theistareykir	48.76	14.98	10.25	11.45	13.22	1.42	0.053	0.685	0.168	0.045	1.5	27.1	15.0	0.513098	1
TH8	Theistareykir	47.62	14.96	10.45	12.40	12.32	1.44	0.033	0.753	0.175	0.037	1.4	29.3	15.8		10
TH15*	Theistareykir	46.34	11.70	10.40	19.00	10.60	1.20	0.120	0.520	0.160	0.140	1.5	33.0	16.0	0.513073	6

Table 1. (continued)

Sample	Location	SiO_2	Al_2O_3	Fe_2O_3T	MgO	CaO	Na_2O	K_2O	TiO2	MnO	P_2O_5	Nb	Zr	Y	$^{143}Nd/^{144}Nd$	Ref.
TH29	Theistareykir	47.47	13.41	9.13	15.73	12.50	1.13	0.011	0.502	0.155	0.024	0.5	16.7	12.0	0.513133	6
9309	Theistareykir	48.04	14.29	10.98	12.26	12.21	1.70	0.057	0.802	0.169	0.049	1.8	32.5	18.6		10
9312	Theistareykir	48.56	13.84	10.40	13.27	12.59	1.51	0.054	0.717	0.165	0.043	1.5	29.0	16.7		10
9313	Theistareykir	47.45	13.16	10.32	15.67	11.58	1.43	0.049	0.612	0.160	0.041	1.3	24.4	14.1		10
9314	Theistareykir	49.21	14.43	10.26	13.44	12.75	1.57	0.052	0.683	0.161	0.045	1.6	27.5	15.9		10
9335	Theistareykir	48.47	13.73	10.30	13.73	12.45	1.51	0.047	0.658	0.168	0.040	1.5	26.5	15.9		10
9352	Theistareykir	48.80	17.16	9.73	8.24	13.82	1.75	0.044	0.739	0.156	0.049	1.8	30.8	16.5		10
9354	Theistareykir	48.31	14.18	10.47	12.99	12.48	1.58	0.049	0.690	0.165	0.044	1.5	27.6	15.3		10
9356	Theistareykir	48.31	13.23	9.68	14.28	12.81	1.35	0.033	0.566	0.160	0.031	1.1	20.3	14.4		10
9370	Theistareykir	47.65	14.46	10.40	13.59	11.95	1.70	0.031	0.736	0.172	0.017	1.2	30.1	18.3		10
9371	Theistareykir	48.65	15.40	10.97	9.81	13.09	1.76	0.051	0.831	0.174	0.053	1.9	32.3	19.1		10
9372	Theistareykir	48.13	15.42	10.60	11.21	12.72	1.70	0.041	0.779	0.171	0.050	1.7	31.0	18.5		10
9375	Theistareykir	48.70	14.49	10.55	11.09	13.16	1.60	0.051	0.749	0.171	0.045	1.5	30.4	17.7		10
9377	Theistareykir	47.47	14.60	10.96	12.48	12.12	1.65	0.041	0.787	0.175	0.050	1.7	32.0	17.8		10
9379	Theistareykir	48.03	15.67	10.38	10.58	13.04	1.73	0.034	0.767	0.165	0.048	1.7	29.6	18.0		10
9381	Theistareykir	46.80	12.03	9.89	18.67	11.23	1.20	0.012	0.495	0.156	0.027	0.6	16.9	14.0		10
9389	Theistareykir	48.78	17.41	9.90	7.81	13.77	1.78	0.054	0.824	0.159	0.059	2.1	36.0	17.3		10
9390	Theistareykir	46.03	11.04	9.83	21.51	10.23	1.10	0.010	0.418	0.158	0.023	0.5	14.0	11.8		10
9391	Theistareykir	46.51	11.64	9.86	20.12	10.67	1.17	0.011	0.462	0.164	0.027	0.5	15.5	13.0		10
9394	Theistareykir	48.12	13.87	10.71	13.83	11.95	1.57	0.048	0.761	0.175	0.046	1.4	30.0	17.2		10
9395	Theistareykir	48.27	15.03	10.49	11.67	12.64	1.72	0.038	0.764	0.171	0.019	1.3	30.9	18.6		10
9397	Theistareykir	46.36	11.58	9.77	20.10	10.65	1.22	0.014	0.459	0.155	0.024	0.4	15.6	13.1		10
9409	Theistareykir	48.54	14.48	9.90	12.07	12.85	1.50	0.049	0.614	0.172	0.009	1.6	26.7	15.2		10
9416	Theistareykir	49.17	15.46	10.75	9.37	12.81	1.83	0.074	0.743	0.183	0.022	2.0	34.2	16.9		10
9435	Theistareykir	48.45	13.63	10.14	13.41	12.58	1.57	0.045	0.646	0.172	0.012	1.4	27.4	16.0		10
9476	Theistareykir	48.28	15.00	10.53	12.18	12.42	1.81	0.040	0.771	0.171	0.022	1.7	33.4	18.7		10
94112	Theistareykir	48.55	14.24	10.61	12.24	12.58	1.66	0.049	0.751	0.173	0.015	1.5	31.6	17.8		10

[a] Major elements are in weight %; Nb, Zr and Y in ppm; Fe_2O_3T is total Fe expressed as Fe_2O_3. All samples, except those marked * [from *Hémond et al.*, 1993] and RP samples [from *Gee*, 1999], were analysed for major and trace elements by XRF in Edinburgh (see *Fitton et al.* [1998] for analytical methods and precision estimates). Nb data given to two decimal places are averages of five individual determinations. Sources of isotope and other information: (1) *Elliott et al.* [1991]; (2) *Zindler et al.* [1979]; (3) *Jakobsson et al.* [1978]; (4) *Gee et al.* [1998]; (5) *Gee* [1999]; (6) *Hémond et al.* [1993]; (7) *B.S. Hardarson and J.G. Fitton* (unpublished); (8) *Hardarson and Fitton* [1997]; (9) *Nicholson* [1990]; (10) *Slater et al.* [2001].

stored and homogenized in large magma reservoirs, hence their very uniform composition [*Hardarson and Fitton*, 1997]. These flows are frequently large enough to flow out of the rift axis and onto the flanks where they will form the upper part of the future lava pile. In our view, both the enriched and depleted components of the mantle beneath Iceland form part of the Iceland plume. *Hanan et al.* [2000], however, disagree and believe that the depleted component is the ambient NMORB source. The data in Figure 1 can be interpreted either way, but in the next section we will show how the Nb-Zr-Y systematics of Icelandic basalt can be used to resolve this issue.

4. Nb-Zr-Y Systematics

[13] A logarithmic plot of Nb/Y versus Zr/Y (Figure 3a) provides a useful discriminant between Icelandic basalt and NMORB (i.e. plume and non-plume basalt). The discriminant works because data from the two types of basalt define separate and parallel linear arrays. Using the lower limit of the Iceland data array as a reference line, *Fitton et al.* [1997] defined a parameter (ΔNb) that expresses excess or deficiency in Nb such that Icelandic basalt has ΔNb > 0 and NMORB has ΔNb < 0. Variation along each array is caused, in part, by variable degrees of melting such that the smallest degrees result in the highest values of each ratio. Thus, data from basalt erupted off-axis in Iceland (e.g. Snæfellsnes) plot at the high-Zr/Y end of the Iceland array, and those from NMORB on slow-spreading segments of the Southwest Indian Ridge plot at the high-Zr/Y end of the NMORB array. *Fitton et al.* [1997] showed that simple melting models can satisfactorily reproduce the slope of these two arrays and that ΔNb is insensitive to degree of melting and must, therefore, be characteristic of the mantle source. It is not, as *Hanan et al.* [2000] say, "merely, in disguise, a complex proxy for the Nb/Zr variation". ΔNb, by definition, shows no systematic variation along the Iceland array (Figure 3a) while Nb/Zr varies by more than an order of magnitude (0.02–0.3; Figures 1 and 3b).

[14] In addition to degree of melting, mantle heterogeneity must contribute to the Iceland array in Figure 3a because radiogenic isotope ratios change systematically along it. For example, Nb/Zr increases from left to right along the array (Figure 3b) and varies inversely with ^{143}Nd/^{144}Nd (Figure 1). The implication is that the depleted and the enriched components in the mantle beneath Iceland must both lie within the Iceland array. Thus, with advanced dynamic melting and melt extraction, the melts become progressively biased towards the depleted component; that is, towards the low-Zr/Y end of the Iceland array (Figure 3b).

[15] Figure 3b is a simplified version of Figure 3a and represents the *Hanan et al.* [2000] data by a single curve fitted to their data array. It is readily apparent why these authors reached the conclusion that variation in their Iceland data can be explained by mixing between plume and NMORB mantle without the need for a DIP component. Their data array passes close to the average composition of large-volume normal Icelandic basalt (Nb/Zr = 0.11; yellow circle in Figure 3b) but they have simply not included data from any samples of depleted Icelandic basalt. Our data for depleted Icelandic basalt (red circles in Figure 3b; data in Table 1) plot away from the *Hanan et al.* [2000] data array and cannot be accounted for by their mixing model. Because these depleted basalts plot within the Iceland array (positive ΔNb), they are clearly distinguishable from NMORB (negative ΔNb; Figure 3b). They are isotopically distinct from other Icelandic basalts (Figure 1) and therefore require the existence of a depleted component in the mantle source beneath Iceland. No known melting process that can generate the two mantle arrays will also be able generate depleted Icelandic basalt from the NMORB source. Because the depleted mantle beneath Iceland is distinct from NMORB-source mantle, commonly interpreted to be the ambient upper mantle, it must form an intrinsic component of the Iceland plume. Our data, therefore, point clearly to the existence of a DIP component.

[16] To summarise

1. Depleted Icelandic basalt is clearly distinguished from NMORB on a plot of Nb/Y vs. Zr/Y. Although the former have very low abundances of

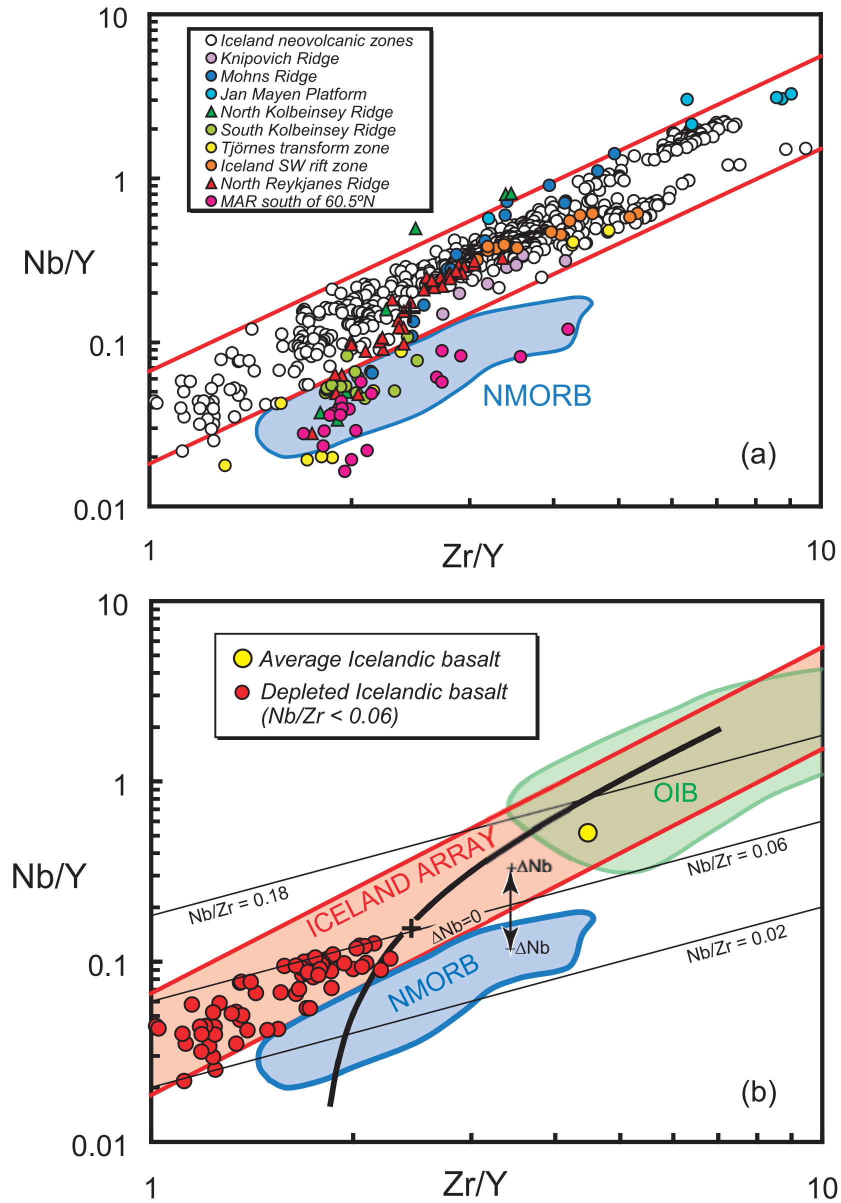

Figure 3. Nb/Y and Zr/Y variation [after *Fitton et al.*, 1997] for basalts (MgO >5 wt.%) from Iceland and the Mid-Atlantic Ridge showing the limits of the Iceland array (red lines). The NMORB field (blue; from *Fitton et al.* [1997]) is based on data from the Reykjanes Ridge (S of 61°N), the East Pacific Rise, and the Southwest Indian Ridge. The + symbol represents an estimate of primitive mantle composition [*McDonough and Sun*, 1995]. (a) Icelandic basalt data (white circles) from *Fitton et al.* [1997], with additional data from *Gee* [1999] and *Slater et al.* [2001]. Data from *Hanan et al.* [2000] are represented by coloured symbols. (b) The *Hanan et al.* [2000] data array is represented by the black curve (fitted by polynomial regression). Average Icelandic basalt composition is based on 78 analyses of large (>0.5 km^3) flows from the neovolcanic rift zones [*Hardarson and Fitton*, 1997]. The OIB (ocean-island basalt) field encloses data from 780 samples of basalt (MgO > 5 wt.%) representing all major ocean islands (J.G. Fitton and D. James, unpublished data, 2000). Note that most OIB plot within the Iceland array, suggesting that the array reflects the composition of plume mantle in general.

incompatible elements, they have an excess of Nb (ΔNb > 0) compared with NMORB.

2. ΔNb is a characteristic of the mantle source and not merely a proxy for Nb/Zr.

3. The Iceland plume mantle probably consists of streaks or blobs of enriched material set in a depleted matrix. Both of the plume mantle end members have positive ΔNb, in contrast to the NMORB source, which has negative ΔNb.

4. The Nb-Zr-Y arguments advanced by *Hanan et al.* [2000] are invalid because they are based on a restricted set of data for Icelandic basalt that completely excludes samples of depleted (i.e. low Zr/Y and Nb/Zr) basalt.

5. The clear compositional differences between depleted Icelandic basalt and NMORB point unambiguously to the presence of a DIP component.

5. Hf-Nd Isotope Systematics

[17] There are two issues here. The first is whether or not it is possible, using combined Hf and Nd isotopes, to distinguish between a depleted plume component and a depleted MORB component. The second, and related, issue is whether or not the Hf-isotope data are sufficiently precise to enable such a distinction to be made. We argue that the answer to both of these questions is a clear, unequivocal, "yes."

[18] We use the standard Hf-Nd isotope plot to illustrate our argument (Figure 4). Ever since Hf-isotope data have been produced, most workers have recognized a "depleted" high εNd and εHf mantle component that is identified with an idealised MORB-source end-member [e.g., *Johnson and Beard*, 1993]. However, the precise location of this depleted component on the εHf-εNd diagram has become contentious, simply because the pre-1997 MORB Hf-isotope data set produced a diffuse field spanning more than 15 εHf units (field A on Figure 4). There were two reasons for this dispersion. Firstly, the error bars on individual Hf-isotope measurements were large, due to the analytical techniques in use before that time. Secondly, some of the MORB samples were obtained from ridge segments that were influenced by hotspots.

[19] By careful selection of samples [*Kempton et al.*, 2000], and by using state-of-the-art analytical methods (below), the NMORB field shrinks to ~6 εHf units (field C on Figure 4), and falls in the lower part of the original MORB field. Furthermore, εNd and εHf now correlate rather than being decoupled [*Kempton et al.*, 2000]. Error bars on individual sample analyses are substantially reduced. However, several samples from Iceland and from older parts of the NAIP have significantly higher εHf and are analytically distinguishable from the field of NMORB. These basalts are clearly not derived from the same mantle as NMORB. Rather, they must come from a distinct, depleted mantle source which, we argue, is intrinsic to the plume itself [*Kempton et al.*, 2000]. For reasons discussed by *Kempton et al.* [2000], this source has evolved with long-term high Lu/Hf, and has remained isolated from the NMORB-source mantle.

[20] *Hanan et al.* [2000] dismiss the Hf-isotope evidence for the depleted plume component by implying that the data produced by *Kempton et al.* [1998] are in error. Specifically, the measured ^{176}Hf/^{177}Hf ratio may be higher than the true value because of an interference by ^{176}Yb on ^{176}Hf. This interference must be adequately accounted for, or the interfering Yb removed from the sample solutions prior to mass spectrometry.

[21] *Kempton et al.* [2000] explain in some detail that two high ^{176}Hf/^{177}Hf values reported in a conference abstract [*Kempton et al.*, 1998] were subsequently found to be in error because of inadequate correction for rare-earth-element (REE) interferences during mass spectrometry. Neither of these data values has been used in any subsequent paper. The error occurred when analytical protocols shifted from thermal ionization mass spectrometry (TIMS) to plasma ionization multi-collector mass spectrometry (PIMMS) in the NERC Isotope Geosciences Laboratory. At this time, the third column separation stage required for Hf analysis by TIMS was omitted for PIMMS work, following the recommendation of *Blichert-Toft et al.* [1997]. However, we found that significant interference of ^{176}Yb on ^{176}Hf could occur for some samples, indicating that our first two column stages did not separate ^{176}Yb (and ^{176}Lu) from ^{176}Hf sufficiently

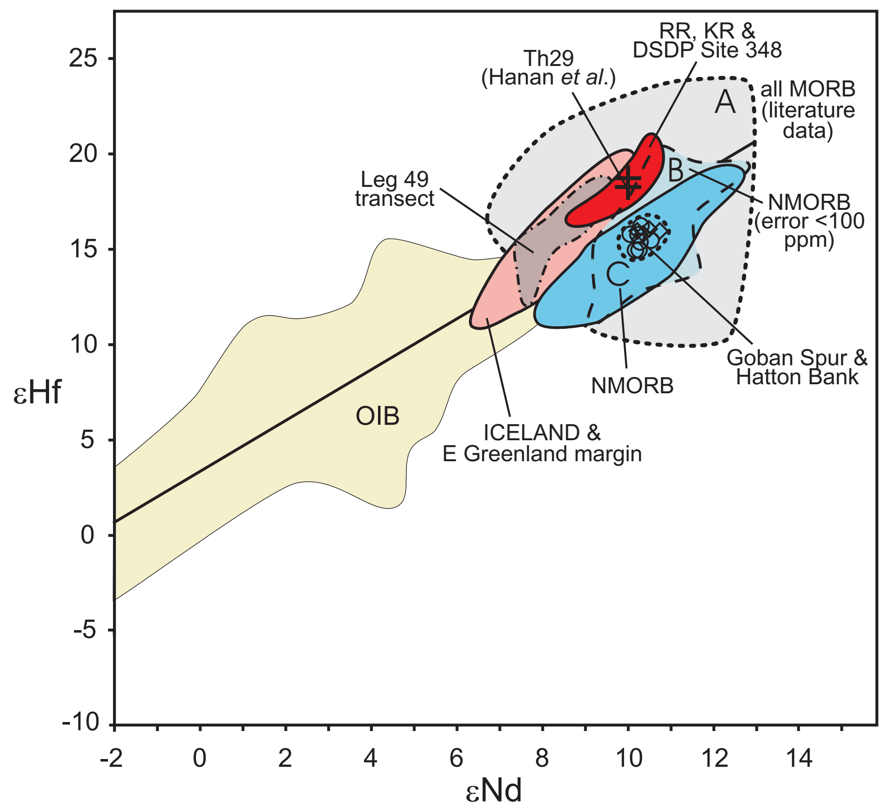

Figure 4. εHf vs. εNd for basalts from the North Atlantic Igneous Province compared with global fields for ocean island basalt (OIB) [*Nowell et al.*, 1998] and MORB. The large grey field with the dotted outline (labelled A) is the field for all MORB data from the literature (data sources in *Nowell et al.* [1998]). The light-blue field with the dashed outline (labelled B) is based on the MORB data in field A, but filtered to exclude analyses having within-run standard errors greater than 100 ppm (±0.000028 in $^{176}Hf/^{177}Hf$). The blue field with the solid border (labelled C) is the field for NMORB (non-plume) based on recent high-precision PIMMS data from *Chauvel and Blichert-Toft* [2001] and *Kempton et al.* [2002], plus the high-precision TIMS data in *Nowell et al.* [1998]. The 2σ uncertainty in these high-precision data is ∼0.5 εHf units. Large unfilled circles and diamonds represent data for Goban Spur and Hatton Bank (off the SW and NW UK continental margins, respectively) [*Kempton et al.*, 2000]. Note that basalts from Iceland and the adjacent Reykjanes (RR) and Kolbeinsey (KR) ridges (Figure 2) define an array that is distinct from that of plume-free NMORB (field C). Data from the depleted Icelandic basalt sample Th29 [*Hanan et al.*, 2000] plot at the depleted end of the Iceland array, and not in the NMORB field.

in all cases. For this reason, we now routinely pass samples through a third stage column to ensure that the Hf fractions are free of REEs. We reported this observation [*Kempton et al.*, 1999, 2000] because the number of laboratories measuring Hf-isotope ratios is increasing, and we wanted others to be aware of this potential problem. We did not expect that it would be used as an unfair means of dismissing our work.

[22] The PIMMS Hf-isotope data reported by *Kempton et al.* [2000] were all carefully monitored for Yb interference and many were analyzed in duplicate. We also repeated most of our original TIMS measurements in order to maintain an internally consistent data set; this includes most samples from the NAIP and some Pacific MORBs reported by *Nowell et al.* [1998]. Within-run standard errors for our PIMMS Hf-isotope analyses are normally less than 22 ppm (2σ). Minimum uncertainties are derived from external precision of standard measurements that average 58 ppm (2σ). Replicate analysis of our internal rock standard, pk-G-D12, yields 0.283049 ± 16 (2σ, n = 22),

which is indistinguishable from our previously reported value determined by TIMS [*Nowell et al.*, 1998] (0.283046 ± 16, 2σ, n = 9). This analytical precision is significantly better than most of the published data for MORB and previously published data for Iceland [*Kempton et al.*, 2000]. As a result, in our analysis of Iceland and other parts of the NAIP, we have excluded all published data having a within-run standard error greater than 100 ppm (equivalent to ∼±0.000028 in $^{176}Hf/^{177}Hf$). Even this generous cut-off is approximately twice our external analytical uncertainly and five times our own typical within-run precision.

[23] The high-precision Hf-isotope data presented by *Kempton et al.* [2000] clearly show that NMORB-source mantle is not the depleted component within the Iceland plume (Figure 4). Basalts from the Iceland neovolcanic zone form a linear trend, with εHf ranging from +11.2 to +19.4 and εNd from +6.5 to +9.7. Basalts from the Reykjanes Ridge overlap the Iceland array, but extend to more radiogenic compositions (εHf values up to +20.5). Samples from the Kolbeinsey Ridge, and their older equivalents (∼19 Ma) from the Deep Sea Drilling Project (DSDP) Site 348, overlap the Reykjanes trend, but with a restricted range in εNd values of +10.4 to +10.5. Basalts from the DSDP Leg 49 transect (on the north-west flank of the Reykjanes Ridge, south-west of Iceland) and the East Greenland margin plot within the Iceland array.

[24] In contrast, North Atlantic NMORB from Goban Spur and Hatton Bank (Figure 4) form a tight cluster within the field of MORB data defined on the basis of data from the literature (field B). Although basalts from the Reykjanes Ridge and Kolbeinsey Ridge slightly overlap the field of MORB based on data from the literature, they plot with significantly higher εHf values than basalts from Hatton Bank or Goban Spur, which are more relevant examples of NMORB for the North Atlantic. These data provide strong evidence that not only does the Iceland plume contain both a depleted and an enriched component, but also that the depleted component is distinct from the NMORB source available prior to plume initiation.

[25] To summarise

1. There is no justification whatsoever for dismissing the concept of a depleted Iceland plume component on the basis of erroneous $^{176}Hf/^{177}Hf$ analyses [*Nowell et al.*, 1998].
2. By using state-of-the-art laboratory procedures, and by carefully analyzing MORB, and basalt from Iceland and other parts of the NAIP using the same procedures, we have reconfirmed that the Iceland plume contains an isotopically depleted component that is distinct from NMORB-source mantle in εHf-εNd space [*Kempton et al.*, 2000].
3. Our study also demonstrates that it is vital, when comparing data from various sources, that these sources are clearly indicated. This is particularly important when older, less precise $^{176}Hf/^{177}Hf$ NMORB data are plotted alongside more modern data [e.g., *Hanan et al.*, 2000, Figures 10 and 11].

6. Conclusions

[26] We have shown that depleted basalt from Iceland differs significantly from NMORB in its Nb-Zr-Y systematics and Hf-isotope ratios, and that this observation requires the existence of a depleted Iceland plume (DIP) component. This conclusion contradicts an assertion made by *Hanan et al.* [2000] that the NMORB source is the depleted component in Icelandic basalt and that a DIP component is not required. The difference in our conclusions is due to differences in our respective data sets. The *Hanan et al.* [2000] trace-element data set contains no data from depleted Icelandic basalt and so it is not surprising that they find no evidence for a DIP component. Their Hf-isotope argument is based on two analyses of a single depleted Icelandic basalt sample (Th29; Table 1), a sample not included in their trace-element set. These two Hf analyses plot within their field for NMORB on an εHf vs. εNd diagram. However, data presented by *Kempton et al.* [2000] define smaller and distinct fields for NMORB and depleted Icelandic basalt. We can now show that the two analyses plot with other depleted Icelandic basalt samples. We conclude, therefore, that the answer to the question raised by *Hanan et al.* [2000] ("Depleted Iceland mantle plume geochem-

ical signature: artifact of multicomponent mixing?") is an emphatic "no". Our data require the existence of a DIP component, and we see no evidence for the involvement of the NMORB mantle source in the generation of Icelandic magmas. The Iceland plume is heterogeneous and probably consists of streaks or blobs of enriched and relatively fusible material in a depleted and refractory matrix. The most likely source for the material forming the Iceland plume is ancient recycled oceanic lithosphere [e.g., *Hofmann and White*, 1982; *Fitton et al.*, 1997; *Chauvel and Hémond*, 2000], and ancient, depleted oceanic lithospheric mantle provides a plausible source for the DIP component [*Skovgaard et al.*, 2001]. Icelandic basalt mostly represents a weighted average of the enriched and depleted components. Melts produced during the advanced stages of dynamic melting, however, will be biased towards the depleted refractory matrix. These depleted melts occasionally reach the surface as small-volume flows of primitive basalt, which are confined to the rift axes.

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